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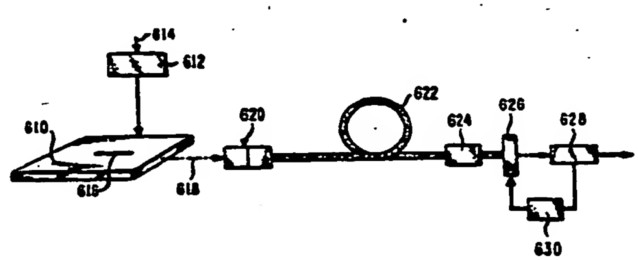
(54) FSK optical communication system.

(57) A light source (610) comprising a source of radiation such as a single-electrode distributed feedback semiconductor laser diode is frequency modulated by direct current modulation with no pre-equalization or pre-distortion of the signal, and the optical signal is coupled to and carried by an optical fiber (622) to a remote location. At the remote location, an optical discriminator (626) such as a fiber Fabry-Perot interferometer can be used for both channel selection where more than one channel is being carried by the optical fiber and for covering the frequency modulation signal of each channel to an amplitude modulated signal. The amplitude modulated signal can be detected by a direct detection receiver (628). In those instances where signal enhancement is required, such as in long-haul lightwave transmission systems, an optical amplifier (624) can be substituted for the normally mandatory regenerator located at the repeater stations.

FIG. 1



EP 0 381 341 A2

FSK OPTICAL COMMUNICATION SYSTEM

Background of the Invention

1. Field of the Invention

This invention relates to frequency shift key (FSK) modulation optical communication systems.

2. Description of the prior art

Optical communications systems are currently of commercial importance because of their ability to carry large amounts of information. Optical communication systems normally have a light source optically coupled to a photodetector via an optical fiber. Systems presently in use carry information at rates which are in excess of 100 Mbits/sec and, it is believed that future systems will carry information at very much higher rates.

For the higher transmission rates and greater distances between the light source and the photodetector, the light source currently preferred by those skilled in the art is a semiconductor laser diode. These diodes are relatively compact and can emit radiation with a relatively narrow spectral width in the wavelength regions presently of greatest interest. Diodes can now be fabricated having both single transverse and single longitudinal mode output. Such diodes are commonly referred to as single frequency lasers. These diodes are desirable in many applications because they, for example, maximize light coupled into the fiber and, at the same time, minimize the deleterious aspects of the fiber chromatic dispersion. Chromatic dispersion may broaden the light pulse which results in limiting the attainable bit rate and distance between the source and the photodetector. If either the bit rate or the distance between the source and the photodetector becomes too great, adjacent light pulses will overlap as a result of fiber dispersion and information will be lost. Normally, to avoid a loss of information due to dispersion, one or more regenerators will be inserted in the fiber between the source and the photodetector. The regenerator reconstructs the broadened, stretched-out light pulse into a more clearly defined light pulse.

Although a variety of modulation techniques are available, present systems normally use intensity modulation of the laser output to convey information. That is, information is conveyed by variation in the intensity of the light output from the laser. This system is normally referred to as Amplitude Shift Keying (ASK) System.

However, other modulation techniques offer specific advantages over intensity or amplitude shift keyed modulation. For example, higher transmission rates are possible with frequency modulation than are possible with intensity modulation for at least two reasons. First, the combination of the inherent frequency modulation or intensity modulation response with RC parasitics results in a more efficient high frequency response with frequency modulation than with intensity modulation. Second, the roll-off in response above resonance is slower for frequency modulation than for intensity modulation.

Moreover, direct intensity modulation of a semiconductor laser becomes increasingly difficult as the bit rate increases. Direct intensity modulation means that the intensity of the light output is varied by varying the current through the laser. This type of modulation has at least three problems which become significant at high bit rates. First, current modulation sufficient for intensity modulation causes large changes of the semiconductor laser diode wavelength which broadens the spectral width of the emitted radiation. This effect is commonly termed chirp and can be as large as, for example, 0.5nm (five Angstroms). Chirp is often undesirable during intensity modulation because of the dispersive properties of the fiber. Second, intensity modulation of a laser requires a large amount of current, typically more than 60 mA which must be rapidly switched on and off. This switching becomes more difficult as the bit rate increases. Third, unless special precautions are taken, many single frequency lasers cannot be fully intensity modulated because of laser mode hopping - the laser output shifts from one longitudinal mode to another. This is commonly referred to as the "extinction ratio penalty".

Because of these reasons, alternatives to direct intensity modulation have been considered. One alternative commonly contemplated is the use of an external modulator positioned adjacent to the laser which might be, for example, an integrated optic modulator. The laser emits radiation continuously and the desired intensity modulation is supplied by signals to the modulator which vary light absorption within the modulator. Potentials normally greater than ten volts are often required for efficient operation of external modulators currently contemplated for use at high frequencies. The voltages required generally increase as the frequency increases. Additionally, there is the problem of obtaining simple, efficient, high speed modulators. There is also the additional problem of signal loss which results from the coupling between the laser and modulator as well as between the modulator

and the optical fiber.

Another approach uses coherent optical techniques which require frequency locking two oscillators separated by an intermediate frequency (IF). While high sensitivity is obtained, locking the oscillators together can be difficult as they may be at diverse locations which can be as far as 100 km apart. In addition, processing of the IF signal adds complexity to the receiver.

Brief description of the invention

In the invention as claimed conversion from frequency modulation to amplitude modulation is carried out in the optical domain.

In the system to be particularly described, a light source comprising a source of radiation such as a single-electrode distributed feedback semiconductor laser diode is frequency modulated by direct current modulation with no pre-equalization or pre-distortion of the signal, and the optical signal is coupled to and carried by an optical fiber to a remote location. At the remote location, an optical discriminator such as a fiber Fabry-Perot interferometer can be used for both channel selection where more than one channel is being carried by the optical fiber and for converting the frequency modulated signal of each channel to an amplitude modulated signal. The amplitude modulated signal can be detected by a direct detection receiver. In those instances where signal enhancement is required, such as in long-haul lightwave transmission systems, an optical amplifier can be substituted for the normally mandatory regenerator located at the repeater stations. In those instances where several frequency modulated channels are wavelength division multiplexed onto a single fiber path, a single optical amplifier can be used to replace all the regenerators at a repeater station.

Brief Description of the Drawing

In the attached drawing:

FIG. 1 is a schematic representation of a frequency modulated system embodying the invention;

FIG. 2 illustrates a plot of the spectrum of the output signal of a frequency modulated semiconductor laser superimposed on the plot of the transmission spectrum of a Fabry-Perot interferometer used to demodulate the signal;

FIG. 3 is a plot of the eye diagram of the demodulated signal, and

FIG. 4 is a schematic representation of a multiple channel WDM system embodying the invention.

Detailed Description

A frequency-shift keyed modulated light transmission system embodying this invention, is schematically depicted in FIG. 1. FIG. 1 illustrates an optical transmission system in which a single unstabilized laser is coupled to transmit an FSK signal along an optical fiber to a remote location where the received FSK signal is demodulated to an ASK signal by a fiber Fabry-Perot interferometer and the ASK output of the fiber Fabry-Perot interferometer is detected by an optical detector. Referring to FIG. 1, the light source comprises a semiconductor laser diode 610 and means 612 for shifting the frequency of said diode in accordance with information received on line 614. One realization of means 612 is modulation of the injection current to the laser. The modulation current is varied to obtain the desired frequency shift. The laser diode has an active region 616 in which electrons and holes recombine radiactively. The frequency modulated beam from the laser is indicated as 618 and is incident upon and passes through two Faraday isolators 620 which provide over 60 dB optical isolation. The optical signal then passes through an optical fiber transmission path 622, an optical amplifier 624, if required, and an optical discriminator which may be selectively variable such as a Fabry-Perot interferometer 626. A direct detection receiver 628 is coupled to receive and detect the optical signal which passes through the Fabry-Perot interferometer. The Fabry-Perot interferometer can be frequency-locked to the frequency of one of the logic levels, for example logic "1", of the frequency shift keyed signal by means of a feedback control 630 coupled between the Fabry-Perot interferometer and the direct detection receiver 628 to maximize receiver photocurrent.

The laser is a single-electrode distributed feedback laser diode which, when in its active state, generates a single longitudinal mode. In operation, the laser is biased well above threshold and the current drive to the laser to shift the frequency to effect Frequency-Shift Keyed modulation is typically much smaller than that which is required for Amplitude-Shift Keying modulation which drives the laser from a high bias level down to or near threshold. The reduction in drive requirements for FSK modulation is very significant at very high bit rates because high-speed, high-power laser driver circuits are difficult to fabricate. In addition, the small drive required for FSK modulation provides a relatively compact laser spectrum which helps to minimize the problems of fiber chromatic dispersion and makes efficient use of the frequency spectrum for Wavelength Division Multiplexing (WDM).

Typically, FSK modulation signals used in heterodyne configurations are electronically demodu-

lated. However, FSK modulation signals can also be optically demodulated by converting the signals to baseband ASK signals and then using a conventional direct-detection receiver. This is an advantage because, with a coherent system, heterodyne detection of high bit rate signals requires large intermediate frequencies and associated wideband electronics.

In operation, a single-electrode Distributed Feedback (DFB) laser diode was frequency modulated by direct current modulation with no pre-equalization at bit rates of 2 Gb/s, 4 Gb/s and 8 Gb/s. The data were optically demodulated at the receiver using Fabry-Perot interferometers. The insertion loss of the Fabry-Perot interferometers used was less than 0.25 dB.

Semiconductor injection lasers normally have a non-uniform frequency modulation response which is caused by competition between thermal modulation and carrier modulation effects. Non-uniform frequency modulation response is not desirable because it results in pattern dependent errors. It is common to compensate for non-uniform frequency modulation response by using a passive network to pre-equalize the modulation signal. Unfortunately, this solution usually results in relatively small frequency modulation response -on the order of 100 MHz/mA - and, therefore, increased drive requirements. Multiple electrode lasers typically have a flat frequency modulation response which is normally less than 1 GHz and, therefore, are not practical for very high data rates.

The above noted problems can be avoided by using a laser that has a relatively large linewidth enhancement factor α (alpha). Lasers having a large linewidth enhancement factor have large linewidth power products, some as high as 500 MHz mW. Large α results in large carrier-mediated frequency modulation responses, for example, up to 2 GHz/mA. A large frequency modulation response provides a double benefit. One benefit is that the drive requirements are small. The other benefit is that the frequency modulation response remains substantially flat to very low frequencies. One such laser diode is a single-electrode distributed feedback laser diode.

Referring to FIG. 2, there is illustrated, as spectrum curve 740, an example of the optical spectrum of a signal Frequency Shift Keyed at a data rate of 2 Gb/s using a 2^{23}-1 pseudorandom word length. The resultant spectrum 740 consists of two peaks 724 and 744. The first peak 724 can be assigned to represent a logic "zero", and the second peak can be assigned to represent a logic "one". The peak-to-peak current drive required was approximately 4 mA and resulted in only about 7% amplitude Modulation.

Superimposed on the Frequency modulation spectrum curve 740 is the transmission response 746 (95% peak transmission) of a 650 um-long Fabry-Perot interferometer with a mirror spacing of 650 um which is used to demodulate the signal. The bandpass of the Fabry-Perot interferometer or cavity is approximately 7GHzFWHM. The bandpass of the Fabry-Perot interferometer, as represented by the transmission response curve 740, will pass the second frequency content 744 and block the first frequency content 742. Thus, the Fabry-Perot interferometer converts the FSK signal to an ASK signal by passing all signals which are representative of a "one" and blocking all signals which are representative of a "zero".

It is to be noted that the method of converting the received FSK signal to an ASK signal by the Fabry-Perot interferometer varies slightly depending on whether the variation of the frequency between the "ones" and the "zeros" of the FSK signal is relatively large or small. In the case of a small frequency variation, conversion to an ASK signal is obtained by moving the FSK signal up and down the side of a discriminator curve. In the embodiment of FIG. 1; the deviation of the frequency between the "ones" and "zeros" of the FSK signal is sufficiently wide to provide two individual peaks. Conversion to an ASK signal is obtained by passing the peaks which represent the "ones" and blocking the peaks which represent the "zeros". By small deviation, it is meant that the deviation of the frequency, the differential of frequency between the "ones" and the "zeros" (f_d) divided by the modulation frequency or bit rate (B) is normally small; on the order of unity. The deviation is considered to be wide when the relationship

$$\frac{f_d}{B}$$

is equal to or greater than one. To optimize the number of channels (N) in a frequency division multiplexed system, the relationship

$$\frac{f_d}{B}$$

should be approximately 3.2. A direct detection receiver coupled to detect the optical signal passed by the Fabry-Perot interferometer can generate clearly distinguishable "zeros" and "ones".

In Electronics Letters, Vol. 21. pp. 504-505, J. Stone discussed a Fabry-Perot design in which the cavity was an optical fiber waveguide with mirrored ends. The free spectral range of the resulting cav-

ity is determined by the length of the fiber segment, and accordingly different free spectral ranges can be obtained by using fibers of different lengths. The cavity can be "tuned" over one free spectral range by changing the cavity optical length by one-half of the wavelength value of the light entering the cavity. In this way the cavity can be "tuned" to resonate at, and therefore transmit, light of different wavelength values. To obtain such tuning, the cavity length can be changed by means of an exemplary piezoelectric element attached to the fiber, which, when activated, will stretch the fiber and increase the associated cavity optical length accordingly.

A tunable Fabry-Perot in which the cavity comprises a fiber portion and a non-waveguiding gap portion is disclosed in EP-A-0300 640.

Referring to FIG. 3,there is illustrated an oscilloscope trace of the resultant eye diagram of the demodulated signal. The horizontal axis corresponds to time at 150 picoseconds/div. The vertical axis corresponds to the output power incident on the direct detection receiver. An examination of the curves of FIG.3 will reveal that no degradation due to non-uniform Frequency Modulation response at low frequencies is evident.

Referring to FIG.4 there is illustrated an expansion of the system of FIG.1, illustrating two separate channels. In this system, an optical coupler (i.e. optical star network, a frequency selective coupler, or the like) can be included to enable the two laser diodes to transmit over a common optical fiber.

The light sources comprise two laser diodes, 950,954, each operating at a distinct frequency, and means 956,958 for shifting the frequency of the associated diode in accordance with information received on lines 960,962. Means 956,958 includes both the bias and modulator currents. The modulation current is varied to obtain the desired frequency shift. The frequency modulated beam from laser 950 is indicated as 964 and is incident upon and passes through two Faraday isolators 968. The frequency modulated beam from the laser 954 is indicated as 966 and is also incident upon and passes through two Faraday isolators 970. The Faraday isolators provide the desired optical isolation. The beams 964,966 are then coupled to a single optical fiber, either passively by means of a beam splitter, a star coupler or directional coupler 971 or by a frequency selective device. The two optical signals traverse transmission path 972 and, if required, an optical amplifier 974. A 3dB coupler, a star coupler or any other beam splitting means 976, located at the receiving end of the optical fiber is coupled to pass a portion of the frequency modulated optical beam to a first Fabry-Perot interferometer 978 and the remainder of the WDM optical beam to a second Fabry-Perot interferometer 980. Direct detection receivers 982,984 are coupled to receive and detect the desired optical signals which pass through their associated Fabry-Perot interferometers. The Fabry-Perot interferometers are frequency-locked to the logic "one" of the frequency shift keyed signals by means of a feedback control 986,988 coupled between the Fabry-Perot interferometer and the direct detection receiver to maximize receiver photocurrent. In operation, the lasers 950 and 954 each generate distinct non-interfering wavelengths and the Fabry-Perot interferometers are designed to pass only the wavelength of interest from its associated laser.

Referring further to FIG. 4, when a multiplicity of laser diodes are used, it may be desirable to use passive star couplers, or frequency selective couplers for the beam splitting means 971,976. In this instance, a passive single mode star coupler or frequency selective coupler can provide network access to a multiplicity of users well in excess of one hundred. Using frequency-division multiplexing, each active user pair can be assigned one of a number of optical carrier frequencies for a session to provide the frequency-division- multiple-access (FDMA) network. It has been determined that channel spacing (f_c) can be as low as 6.4B for a single fiber Fabry-Perot and 3B for two fiber Fabry-Perot in tandem, where B is the bit rate, with negligible power penalty. In addition, the laser linewidth (f_e) should be <0.1B. A network using two 45-M bits/s frequency-shift-keyed laser channels at 1.5 um and having a minimum channel spacing of about 6 times bit rate B operated satisfactorily with a single fiber Fabry-Perot. If a tandem Fabry-Perot cavity is used, then channel spacing can be reduced to approximately 3 times bit rate B. See Electronics Letters, Vol. 23, No. 21,pp. 1102-1103 (October 8, 1987) by I. P. Kaminow, et al.

Estimates show that a network having 1000 users, independent of bit rate, is possible with a tandem fiber Fabry-Perot cavity. For B=1G bit/sec per channel the network capacity can be 1 T bit/s.

The number of channels which are possible for a single Fabry-Perot can be expressed as

$$N=\frac{F}{6.4}$$

where F is finesse value of the single Fabry-Perot.

The number of channels which are possible for a tandem Fabry-Perot of substantially equal length can be expressed as

$N = 0.011F^2$

where F is the effective finesse of the two Fabry-Perots;

and, the number of channels which are possible for a tandem Fabry-Perot of substantially different lengths can be expressed as

$N = 0.03F^2$

where F is the effective finesse of the two Fabry-Perots.

Derivation of the above noted relationship are more fully expressed in the Journal of Lightwave Technology, Vol. 6, No. 9, pp. 1406-1414 (Sept. 1988) by I. P. Kaminow et al.

Thus, there is disclosed a transmission system which comprises Frequency-Shift Keying modulation in combination with optical (incoherent) demodulation using a Fabry-Perot interferometer. Clearly, with Frequency-Shift Keying Modulation, the semiconductor laser is not turned off-and-on and, therefore, the power of the signal being transmitted is relatively constant. Thus, as the power of the signal being transmitted is relatively constant, it is now possible to use an optical amplifier 974 in place of several regenerators at a repeater station for amplifying the multipliciry of wavelength division multiplexed signals being transmitted. As noted above, with Amplitude Shift Keying modulation, the signal being transmitted goes from a minimum value - usually zero - to a relatively large value. Optical amplifiers will give rise to cross talk between the various channels when the signal is Amplitude Shift Key modulated. However, in the optical Frequency Shift Keyed modulation transmission system here disclosed, the optical signal being transmitted does not exhibit large variations of power. Therefore, and particularly if several systems are wavelength division multiplexed onto a single fiber path, an optical amplifier can be used in place of the many regenerators at the various repeater stations. Specifically, the savings in cost per repeater station can be substantial. In addition, if it proves feasible to place optical amplifiers at all repeater stations in a given route, adding capacity to such a route will require adding only additional terminals with terminal generation operating at different wavelengths; repeater stations remain unchanged. Thus, even if the optical amplifier were to cost the same as the regenerator, a savings will be realized.

Thus, with the constant intensity modulation system here disclosed, that being the use of Frequency Shift Keying modulation of lasers and Fabry-Perot interferometer for channel selection and/or Frequency Shift Keying to Amplitude Shift Keying at the receiver - not at the transmitter - it is now possible to have a system which can operate with substantially reduced laser modulation drive current; has the ability to replace regenerators with optical amplifiers: and provides more precise control of the spectrum of the optical beam.

Furthermore, in the case of a transmission system where normally several wavelength division multiplexed channels are transmitted, each with a distinct but fixed frequency, it is possible to use frequency selective couplers to multiplex and demultiplex channels with substantially less loss than would be obtained if a non-frequency selective coupler, such as a star coupler, were used.

Claims

1. An optical communication system comprising
a single frequency laser (610,950),
modulator means (612,958) coupled to frequency modulate the optical signal from said laser and
an optical fiber (622,972) for transmitting the modulated optical signal from said laser to a remote location, CHARACTERISED BY
means (626,978) coupled to said optical fiber at said remote location for demodulating the transmitted frequency modulated optical signals to amplitude modulated signals.

2. An optical communication system in accordance with claim 1 wherein said single frequency laser comprises a single contact single frequency semiconductor laser.

3. An optical communication system in accordance with claim 2 wherein said laser comprises a single contact distributed feedback laser diode.

4. An optical communication system in accordance with any of the preceding claims including an optical receiver (628,982) coupled to receive the amplitude modulated signal from said demodulator.

5. An optical communication system in accordance with claim 4 including feedback control means (630,986) interposed between said demodulating means and said optical receiver to help maximize receiver photocurrent.

6. An optical communication system in accordance with any of the preceding claims wherein said demodulator is a Fabry-Perot interferometer.

7. An optical communication system in accordance with claim 6 wherein said Fabry-Perot interferometer is a fiber Fabry-Perot.

8. An optical communication system in accordance with claim 6 wherein said Fabry-Perot interferometer is a tandem fiber Fabry-Perot.

9. An optical communication system in accordance with any of the preceding claims including an optical amplifier (624) at said remote location coupled to amplify the frequency modulated optical signal.

10. An optical communication system as claimed in any of the preceding claims comprising
a second single frequency laser (954)
a second frequency modulator (958) means coupled to frequency modulate the optical signals from

said second single frequency laser, the optical fiber (972) being arranged for transmitting the frequency modulated optical signals from the first said laser and the second laser to the remote location, and a second demodulation means (980) coupled to said optical fiber at said remote location for demodulating the optical signals from said second laser.

FIG. 1

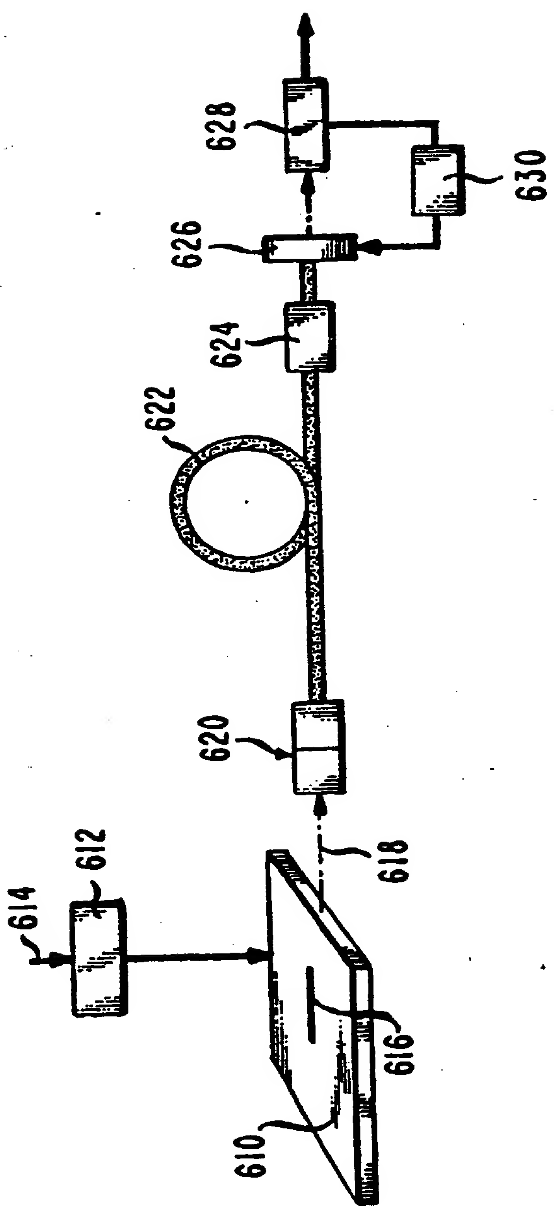


FIG. 2

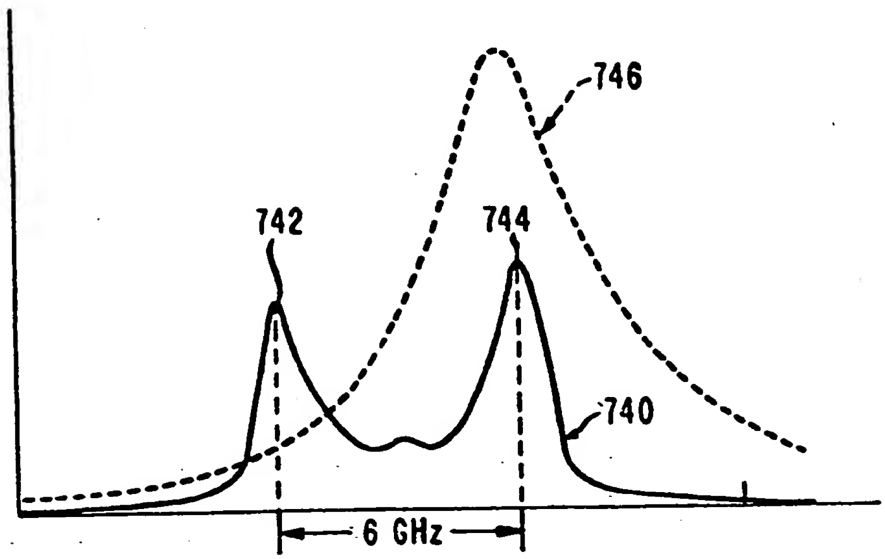


FIG. 3

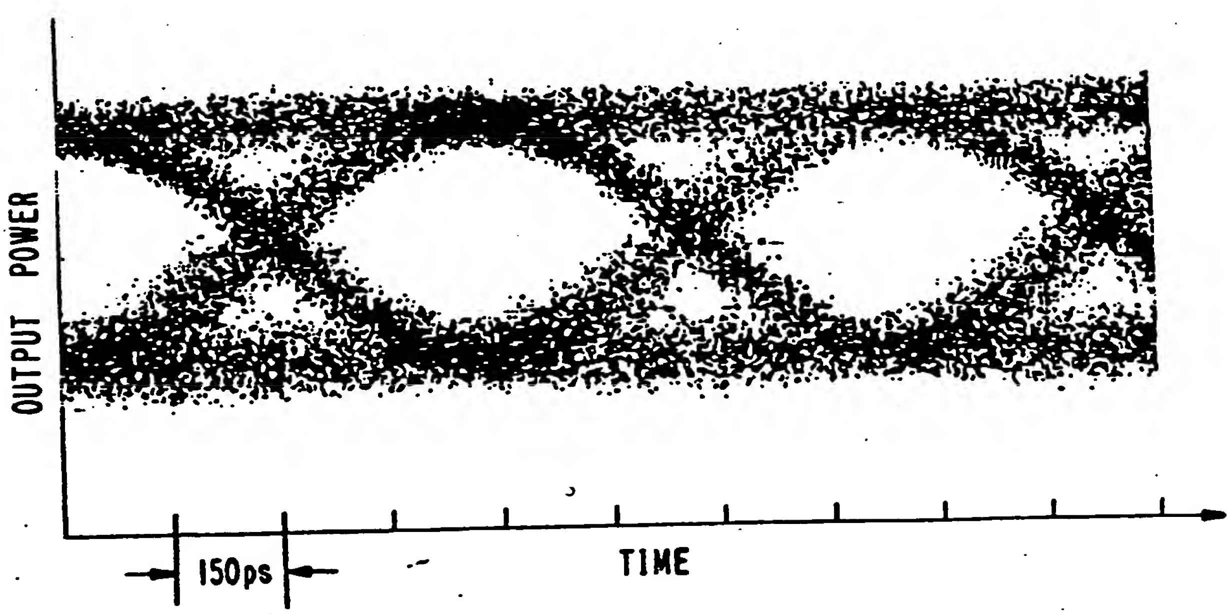


FIG. 4

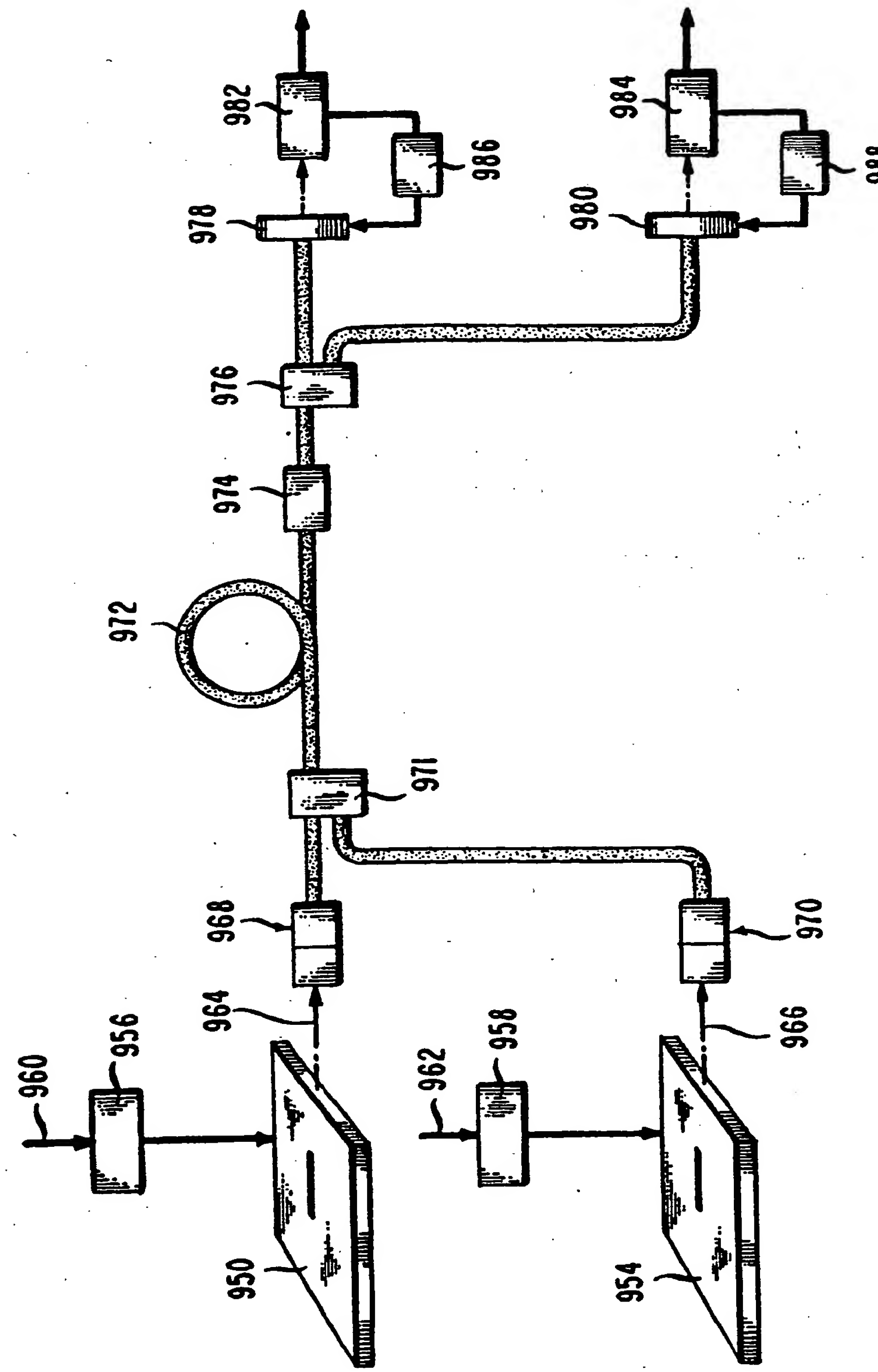

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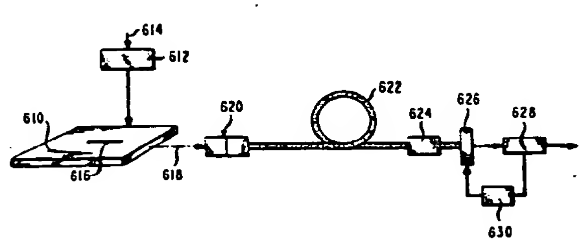
FIG. 1



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EUROPEAN SEARCH REPORT

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EP 90 30 0560
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DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
X	JOURNAL OF LIGHTWAVE TECHNOLOGY vol. 6, no. 9, 1 September 1988, NEW YORK (US) pages 1406 - 1414; I. KAMINOW ET AL.: 'FDMA-FSK star network with a tunable optical filter demultiplexer.'	1,4-8,10	H04J14/02 H04B10/14
Y	* page 1406, column 1, line 10 - page 1406, column 2, line 12 * * page 1406, column 2, line 26 - page 1406, column 2, line 31 * * page 1406, column 2, line 44 - page 1406, column 2, line 47 * * page 1409, column 1, line 1 - page 1409, column 1, line 22 * ---	2,3,9	
X	ELECTRONIC LETTERS vol. 23, no. 9, 1 April 1987, HITCHIN (GB) pages 463 - 464; L.CIMINI ET AL.: 'Optical-fibre Fabry_Perot frequency discriminator for communications applications' * page 463, column 1, line 13 - page 463, column 1, line 17 * * page 463, column 2, line 9 - page 463, column 2, line 29 * ---	1,4-7	TECHNICAL FIELDS SEARCHED (Int. Cl.5) H04J H04B H04L
Y	PROCEEDINGS EUROPEAN CONFERENCE ON OPTICAL COMMUNICATION vol. 3, 13 September 1987, HELSINKI (FL) pages 79 - 78; C. BAACK ET AL.: 'Coherent multicarrier techniques in future broadband communicatio networks' * page 80, line 27 - page 80, line 34 * * page 84; figures 1,7 * --- -/--	9	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	13 DECEMBER 1991	VAN DEN BERG J.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

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DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
Y	SUMMARIES OF PAPERS PRESENTED AT THE OPTICAL FIBER COMMUNICATION/INTERNATIONAL OPTICS AND OPTICAL FIBER COMMUNICATION CONFERENCE 19 January 1987, RENO (US) page 200; HITOSHI KAWAGUCHI ET AL.: 'Experimentel verification of optical demultiplexing using DFB-type LD amplifier.' * in total*	9	
Y	US-A-4 794 608 (TOSHIHIRO FUJITA ET AL.) * column 2, line 51 - column 3, line 60 * * column 11, line 4 - column 11, line 17 * * column 11, line 44 - column 11, line 59 *	2,3	
			TECHNICAL FIELDS SEARCHED (Int. Cl.5)

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	13 DECEMBER 1991	VAN DEN BERG J.

CATEGORY OF CITED DOCUMENTS

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